AD-A205 388

AFRRI TR88-2

AFRRI TECHNICAL REPORT

A low-energy x-ray irradiator for electrophysiological studies

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REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3 DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) AFRRI TR88-2	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION Armed Forces Radiobiology Research Institute 6b. OFFICE SYMBOL (If applicable) AFRRI	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State, and ZIP Code) Defense Nuclear Agency Bethesda, Maryland 20814-5145	7b. ADDRESS (City, State, and ZIP Code)
8a. NAME OF FUNDING/SPONSORING ORGANIZATION Defense Nuclear Agency 8b. OFFICE SYMBOL (If applicable) DNA	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code) Washington, DC 20305	10 SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO.: NWED QAXM PROJECT NO.: TASK NO.: WORK UNIT ACCESSION NO: MJ 00105

11 TITLE (Include Security Classification)
(see cover)

12 PERSONAL AUTHOR(S)
Schauer, D. A., Zeman, G. H., and Pellmar, T. C.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Technical	FROM ____ TO ____	1988 December	34

16 SUPPLEMENTARY NOTATION

17 COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	

19 ABSTRACT (Continue on reverse if necessary and identify by block number)

A 50 kVp molybdenum target/filter x-ray tube was installed inside a lead-shielded Faraday cage. High-dose rates of up to 1.54 Gy/min (17.4 keV weighted average photons) were used to conduct local in vitro irradiations of the hippocampal region of guinea pig brains. Electrophysiological recordings of subtle changes in neuronal activity indicate the system is suitable for this application. (AW)

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☐ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED
22a. NAME OF RESPONSIBLE INDIVIDUAL M. E. Greenville	22b TELEPHONE (Include Area Code): (202)295-3536 22c. OFFICE SYMBOL: ISDP

CONTENTS

INTRODUCTION

High-dose-rate, acute, whole-body exposures have been the main focus of radiobiology research conducted at the Armed Forces Radiobiology Research Institute (AFRRI) for many years. Extensive quantitative studies analyzing behavioral effects, radiation induced syndromes, and combined injury phenomena have been conducted. The sources of radiation used in these studies are the AFRRI TRIGA Mark-F pulsing nuclear reactor, cobalt-60 whole-body facility, and 50-MeV linear accelerator.

Selective irradiation of specific organs has become an area of investigation with emphasis on mechanistic effects. Specifically, cellular and tissue studies have been initiated using the above-mentioned sources. For example, Tolliver and Pellmar (1) initiated a study to evaluate radiation damage to brain neurophysiology. Slices from the hippocampus of guinea pig brains were remotely irradiated *in vitro* and subsequently examined for neuronal damage by means of electrophysiological recording of neuronal activity. The remoteness of the radiation source in relation to the recording chamber presented some inherent limitations in this type of analysis:

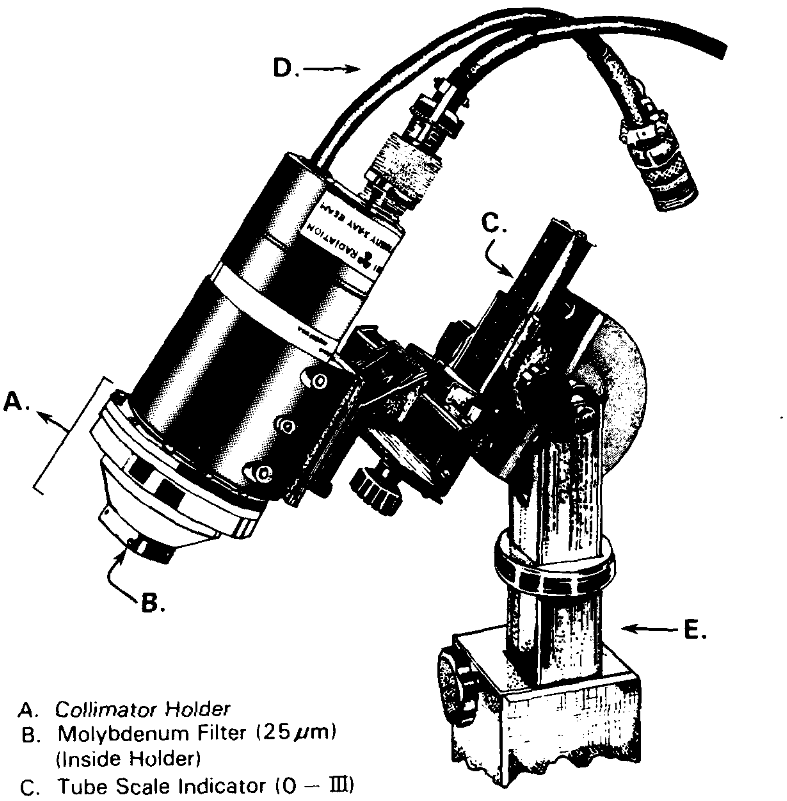
- The analysis of a large number of samples was required, and only large changes could be observed, since electrophysiological responses vary greatly even within the same animal.

- It was not possible to observe early transient neuronal effects because data could only be collected approximately 30 minutes postirradiation.

Despite the above limitations, Tolliver and Pellmar (1) documented statistically significant impairment in the function of the neural tissue at doses as low as 50 Gy with a dose rate of 20 Gy/min. While this research showing direct damage to neural tissue was a significant advance, it was desirable to study the effects of lower doses of radiation at earlier times. To accomplish this end, it was necessary to increase the experimental system's sensitivity by actually conducting tissue irradiations within the electrophysiology recording chamber. If this were possible, each brain slice preparation could act as its own control as the stimulating/recording electrodes remained in place before, during, and after the irradiation. This type of study would eliminate the limitations listed above and allow more subtle neuronal changes to be examined and quantified. A small x-ray unit was therefore set up to operate in a Faraday cage enclosing the electrophysiology recording apparatus.

RADIATION SOURCE

The source of radiation is a Kevex (K5010T) 50-kVp, 1-mA x-ray tube manufactured by Kevex X-ray Tube Division, Scotts Valley, CA (2). The system's key components are an x-ray head, x-ray tube with added molybdenum (Mo) filter, collimators, x-ray tube holder, x-ray source control unit, and cables. (See figures 1 and 2 for schematics of the above components.) A detailed description of the various components follows.



A. *Collimator Holder*
B. Molybdenum Filter (25 μm) (Inside Holder)
C. Tube Scale Indicator (0 – III)
D. High and Low Voltage Connectors
E. Mounting Post

Stainless Steel Collimators

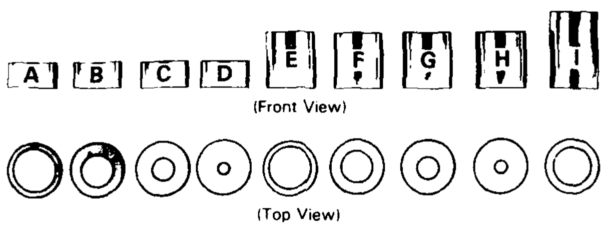


Figure 1. Kevex 50 kVp/1 mA x-ray tube with added Mo filter, tube holder/ precision positioning stand, and stainless steel collimators. Tube is approximately 20 cm in length and 7 cm in diameter. Dimensions of the collimators are as follows: A-D, 15 mm in length, 20-5 mm inner diameter, respectively; E-H, 30 mm in length, 20-5 mm inner diameter, respectively; and I, 40 mm in length, 20 mm inner diameter.

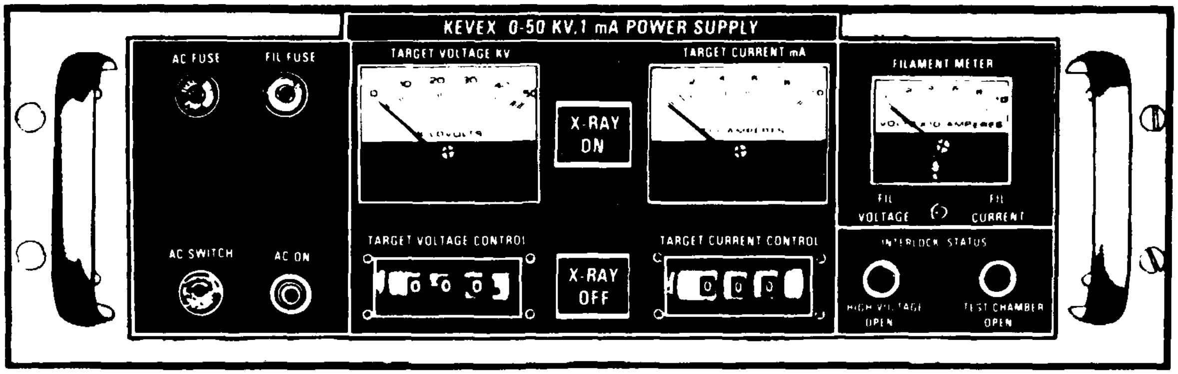


Figure 2. Standard 50 kVp and 1 mA power source.

X-RAY HEAD

The hermetically sealed and completely radiation-shielded x-ray head houses the x-ray tube and high- and low-voltage connectors. For high-voltage insulation and efficient heat conduction, the head is filled with a liquid dielectric. Additionally, a gas bubble is provided to accommodate differential expansion in materials due to heating.

X-RAY TUBE

The x-ray tube consists of a cathode, beam current and electron focal spot control grids, and an Mo transmission target. The oxide-coated, thermionic cathode is an indirectly heated electron emitter controlled by an electrostatic field produced by the grid potential. The first double grid, closest to the cathode, controls the electron beam emission; the second single grid, between the first grid and the target, controls the electron beam spot size. The focal spot grid operates independently from the beam emission grid and can be used to vary spot size from 0.5 to 4 mm in diameter. The transmission target yields x rays emitted in the direction of the longitudinal axis of the x-ray head. These x rays are further filtered with a 25-μm-thick Mo filter, added externally to the end of the tube adjacent to the 127-μm-thick beryllium transmission window. This Mo-Mo configuration should yield a quasi-monoenergetic x-ray spectrum consisting primarily of the approximately 17.4 keV K α x rays of Mo (3) (see table 1).

Table 1. Physical Aspects of the Molybdenum Target and Filter

K Series	Photon Energy (keV)	L Series		Photon Energy (keV)
K α 1	17.478	LIII	L $_\ell$	2.015
K α 2	17.373		L β 2	2.518
K β 1	19.607		L α 1	2.293
K β 2	19.964		LIII ab	2.523
K ab	20.002	LII	L β 1	2.395
			L γ 1	2.623
			LII ab	2.627
		LI	LI ab	2.884

With the 25-μm Mo filter, the predominant radiation should be the K α 1 series (relative intensity of 100) that results from the transition of L III to the K shell. The K α 2 series or the L II to K shell occurs with a relative intensity of approximately 50. The K β series, which is M III and M II to K, is of higher energy than K α; however, the relative intensity is only about 25. Accordingly, the weighted averages (K α = 17.443 keV, K β = 19.663 keV) best describe the energy spectrum anticipated for this tube configuration, with K α most prevalent.

COLLIMATORS

The tube head is modified with an external adapter to hold various collimators (see figure 1) of three different lengths and three different inner diameters.

X-RAY TUBE HOLDER

The tube holder was locally designed and fabricated to allow variation of the tube positioning in the horizontal and vertical axes. By using the positioning indicators as illustrated in figure 1, the distance between the tube and the specimen could be varied to control the dose rate to the sample. This design also affords extremely accurate reproducibility in positioning the unit from run to run.

X-RAY SOURCE CONTROL UNIT

The 115 Vac, 60 Hz control unit consists of a filament grid bias and beam current control, focal spot size control, and high-voltage power supplies along with the control circuitry necessary to provide the settings/limits of operation (figure 2). The kV can be selected in the range 00.0 to 49.9 in steps of 00.1 kV, and the mA in the range 0.00 to 0.99 in steps of 0.01 mA.

CABLES

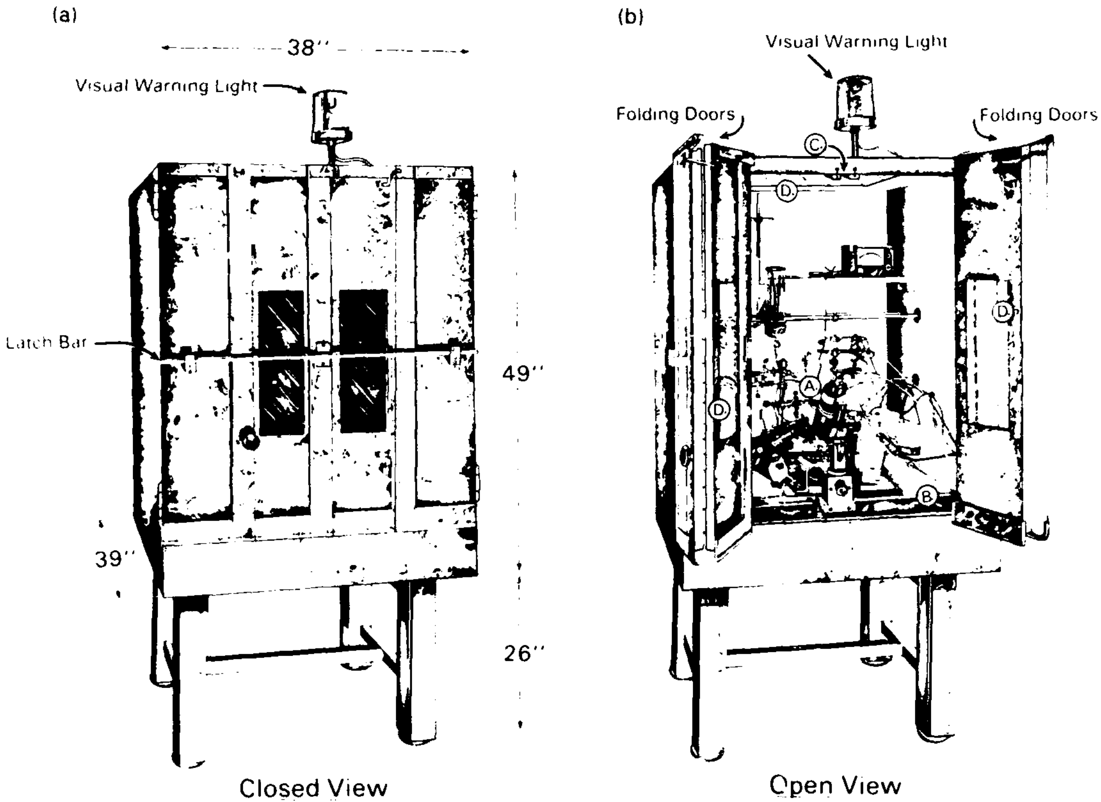
The power supply and tube are interfaced by separate high-voltage and multiconductor low-voltage cables. The cables, which are approximately 2.3 meters long, allow for remote operation of the unit.

IRRADIATION SYSTEM

To meet the unique requirements for this local *in vitro* irradiator, a system was designed in which the irradiation could be conducted inside a Faraday cage enclosing the electrophysiology recording chamber (see figures 3a,b). The purpose of the Faraday cage was to block out any external electromagnetic interference and allow accurate measurement of the low-level electrophysiological potentials. For these experiments, a lead-lined box replaced the standard copper mesh Faraday cage. The box's design and fabrication had to meet radiation safety and operational constraints.

The entire cage was shielded in accordance with the National Council on Radiation Protection and Measurements (NCRP) Report No. 49, "Structural Shielding Design and Evaluation for Medical Use of X-rays and Gamma Rays of Energies up to 10 MeV" (4). The criteria for the shielding design included a highly conservative assumption that the workload for the KEVEX x-ray tube could be as high as to include continuous operations with the beam for up to 10 hours per day, 6 days per week, at maximum voltage (50 kVp) and tube current (1 mA), i.e., W = 3600 mA•min/week, and that occupancy by members of the general public would be possible at any location within 0.4 meter from the tube while it operated within the shield. On the basis of these assumptions, the required shielding thicknesses derived from appendix C, table 8, of NCRP Report No. 49 were 0.75 mm lead (Pb) or 7.5 cm concrete for the primary (direct beam) barrier, and 0.60 mm Pb or 5.5 cm concrete for secondary (leakage/scatter) barriers.

The installed shielding of 1 mm Pb in the walls of the box and the 0.8 mm Pb-equivalent plastic in the window and top of the box met the above criteria. Likewise, the 10-cm-thick marble (density of 2.47-2.86 g/cm^3) table top was even more massive than the concrete (density 2.35 g/cm^3) thickness required for a primary barrier, so no additional shielding was required on the table top.



A Kevex 50 kVp 1 mA X-Ray Unit
B Base of Interior - 4" Marble (Primary Barrier) *Rests on Air Cushion
C Interlocks
D Clear Pb-plastic
*The Entire Unit is Shielded With Lead Walls (1 mm Thick) (Secondary Barrier)

Figure 3. Lead-shielded Faraday cage: (a) closed view; (b) open view with x-ray tube in place.

Note that the x-ray shielding parameters covered in NCRP Report No. 49 apply to tungsten target x-ray tubes (4). This fact leads to some overestimation of the shielding requirements for an Mo target x-ray tube because the bremsstrahlung x-ray spectrum has reduced output intensity from the lower atomic number target. The highly intense low-energy (17-19 keV) characteristic x rays from Mo do not affect the shield design because they are preferentially absorbed in the initial layers of the shield, compared to the more energetic (20-50 keV) and penetrating bremsstrahlung portion of the x-ray spectrum.

The 0.8 mm Pb-equivalent plastic (Nuclear Associates, Carle Place, NY) used in the window was included to allow the investigator to view the sample during irradiation. The ability to see inside the box during irradiation proved beneficial in aligning the field. To allow ample light into the array, a section of the top of the box was also made of the Pb-equivalent plastic.

Interlock recommendations for an x-ray apparatus are described in NCRP Report No. 88, "Radiation Alarms and Access Control Systems" (5): "Areas containing radiation-producing equipment or sources that could produce potential doses in the high-to-extreme categories should have interlocks as an integral part of their access control system."

An interlock system was designed and installed with the benefit of the interlock jack on the back of the power supply. The system consisted of an interface box between the power supply and the x-ray tube that first had to be turned on to supply power to the system. Additionally, whenever the switch was ON, a red warning light was illuminated. Microswitches were also installed on both doors so that the doors required positive pressure (i.e., both doors secured with a latch bar, as illustrated in figure 3a) before power could be supplied to the unit. The design of this system was "fail-safe" in that if the interlock was violated in any way, all radiation production ceased immediately. Last, when the interlock was tripped, the system required manual resetting to prevent a sudden surge of power to the x-ray tube.

NCRP Report No. 88 (5) also recommends a warning light as a caution to other personnel in the lab that radiation is in progress. Such a light was installed in conjunction with the interlock system. The light is ON whenever power is provided to the unit.

DOSIMETRY PROCEDURES

IONIZATION CHAMBER

A Capintec parallel-plate ionization chamber (Model No. PS-033) was used to determine the exposure rate from the tube. The sensitive volume of the detector was 0.5 cm^3, and the aluminized mylar window was 0.5 mg/cm^2 thick. The diameter of the detector's sensitive area was 16 mm. The detector and electrometer were calibrated at the National Bureau of Standards for two beam codes (L20 and L50) to span the x-ray energy range encountered in these experiments. (See appendix A.) The difference of 2.4 percent between the two calibration factors indicates that the chamber response varies only slightly over a wide spectrum of low energies. The chamber was operated at ±300 volts bias, and all data represent average readings made at opposite polarities, which differed by no more than 0.5 percent.

RADIOGRAPHIC FILM

The x-ray film used in these tests was Kodak X-Omat V film (for therapy verification) in paper packs. The film was exposed at 5 cm from the end of the collimator holder with the tube positioned at the normal operating angle (35^{o} from vertical). Collimators A-I and the open beam were analyzed at a 25 kV and 0.2 mA setting for a 30-second exposure. The open beam density was studied using density scans in the horizontal and vertical axes to quantify the field's consistency and, hence, the exposure rate.

BEAM DIAMETER GAUGE

A fluorescent screen beam diameter gauge (Nuclear Associates Model No. 07-604) was used to position the chamber for measurements taken inside the array. The room and cage were darkened, and the fluorescent screen was placed in the array at the tissue's location. The tube was then powered up, and the beam location and size were viewed through the front panel. This observation provided vital information for the radiation's angle and the chamber's positioning for dosimetry. Accordingly, the sample holder was modified to allow the chamber to be situated in the exact center of the beam where radiograph studies indicated that the exposure rate was constant. Furthermore, the chamber's center coincided with the tissue location during normal radiations, and the top of the chamber was at the same height as the sample. The beam diameter gauge data were confirmed with the radiograph results (addressed further in the Results section). The characterization of the beam using the above techniques allowed for determination of dose rates at various points. Once this information was determined, the chamber was removed and the irradiations were performed for calculated periods of time until the desired doses were delivered.

DOSIMETRY CALCULATIONS

Electrical charge from the parallel-plate ionization chamber was collected using a Keithley 616 electrometer set in the charge (10^{-9} C) mode, which was in turn interfaced with a Hewlett-Packard (HP) data acquisition unit and an HP-85 computer. The exposure (X) in roentgens (R) was calculated from the average of 10 sequential readings taken over 10-second intervals (M) at both polarities with the chamber irradiated free-in-air with no buildup as follows:

$$X = M \bullet N_x \bullet K_q \bullet K_{tp}$$

where N_x was the NBS exposure calibration factor for the chamber in the L50 field (see appendix A), K_q was the electrometer correction factor (see appendix A), and K_{tp} was the temperature (T) and pressure (P) correction factor given by

$$K_{tp} = \frac{273.2 + T\ (^oC)}{295.2} \bullet \frac{760}{P\ (mm\ Hg)}\ .$$

The dose (D_m) was calculated as follows:

$$D_m = X \bullet f_{med}$$

where

$$f_{med} = 0.873 \left[\frac{\mu_{ab}}{\rho}\right]_{air}^{med} \quad \text{for various materials in cGy/R.}$$

For approximately 17.4 keV photons in water, $f_{med} = 0.889$ (6).

An aqueous solution perfused the tissue slices being studied in the electrophysiology recording chamber to maintain tissue viability during the experiments. A dose attenuation factor was applied to account for the thin layer of water covering the sample. On an average, the tissue was under 0.5 mm of water, so the dose to the tissue (D_{mt}) was calculated as follows:

$$D_{mt} = D_m \bullet I/I_o$$

where I/I_o is the correction factor for the attenuation of the primary beam by 0.5 mm of water. Using μ/ρ for approximately 17.4 keV photons in water, the attenuation correction was 0.943 (see table 2). During normal perfusion of the tissue sample, it was estimated that the amount of water on top of the sample could vary by as much as ±0.2 mm. This variance would cause the above attenuation correction factor to vary by ±2.2 percent.

RESULTS

DOSE RATE VERSUS CURRENT

With a constant potential difference setting of 49 kV and the tube positioned at 10.7 cm from the anode to the detector (i.e., Tube Scale Indicator 0), dose rate data were collected for 0.1 mA, 0.3 mA, 0.5 mA, 0.7 mA, 0.9 mA, and 0.99 mA. The increase in radiation output was linear with the increase in current, and figure 4 is a plot of the data acquired. With this inherent linear characteristic, the dose rate from the tube can be changed by varying the current without having to reposition the tube.

Table 2. Table of Mass Attenuation Coefficients (μ/ρ) for Photon Energies 10 keV to 50 keV

Energy (keV)	Medium			
	Lucite	Water	Brain*	Soft Tissue*
10	2.273	5.223	5.338	4.783
15	1.077	1.639	1.687	1.523
17.4 †	0.835	1.244	1.280	1.161
20	0.562	0.796	0.819	0.750
30	0.301	0.372	0.379	0.358
40	0.234	0.267	0.270	0.261
50	0.207	0.226	0.228	0.222

Units: cm^2/g

*As defined by the International Commission on Radiological Protection (ICRP)
†Values based on interpolation

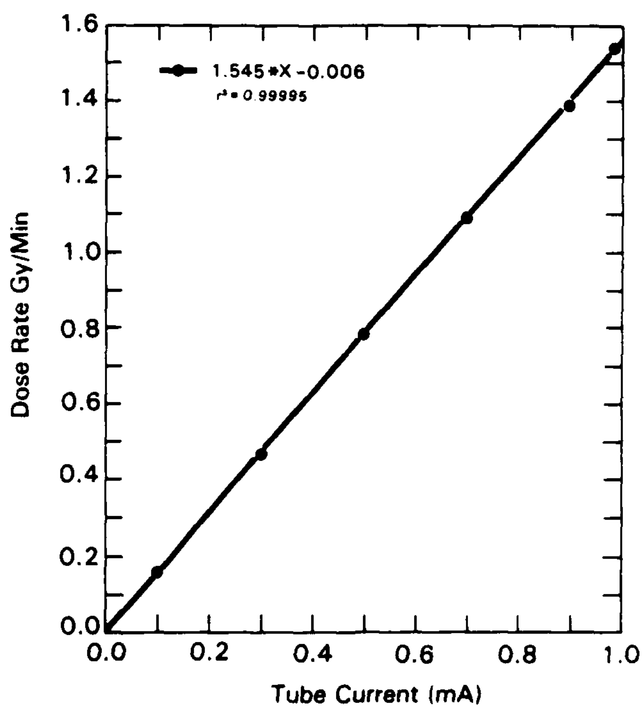


Figure 4. Dose rate vs. current (mA) with a constant potential of 49 kV.

DOSE RATE VERSUS POTENTIAL DIFFERENCE

With a constant current setting dose rate, data were collected for 10 kV, 20 kV, 30 kV, 40 kV, 45 kV, and 49 kV. The data plotted in figure 5 show a curvilinear response for the filtered (25 μm Mo) and the unfiltered configurations. The effect of the 25-μm Mo filter was to reduce the measured dose rate by a factor of 16 at 49 kV to 33 at 20 kV, and to accentuate the curvature of the output curve. In routine use, the unit was set up to operate at a fixed 49 kV.

DOSE RATE VERSUS DISTANCE

Dose rates measured at varying distances from the four tube scale indicators were compared to confirm the expected inverse square behavior of the x radiation. See figure 6 for the plotting of the above data. Table 3 lists the results obtained.

RADIATION QUALITY

Half-value layer (HVL) and homogeneity coefficient are frequently used to describe the quality of an x-ray beam. HVL is the thickness of a material that reduces the exposure rate of the beam to one-half (7). The homogeneity coefficient is the quotient of the thickness of attenuator required to reduce the exposure rate to one-half divided by the thickness of attenuator required to further reduce the exposure rate from one-half to one-fourth. The material used in the 10- to 120-kV range is usually aluminum (Al) (density = $2.70 \cdot 10^3$ kg/m^3) and a chemical purity of >99.8 percent (8). To minimize the number of scattered photons that are detected, narrow-beam geometry or "good geometry" was used. All measurements were made at a distance of approximately 0.5 m focus-to-surface distance with the Al attenuators placed halfway. The tube setting was 49 kV and 0.99 mA, and the 25-μm Mo filter was positioned at the end of the tube.

As plotted in figure 7, the first and second HVL's for the unfiltered beam were 0.1 mm and 0.24 mm, for a homogeneity coefficient of 0.42. For the 25-μm Mo-filtered beam, the first HVL was equal to 0.40 mm Al, and the second HVL was equal to 0.46 mm Al; the homogeneity coefficient for the beam wa therefore 0.87. Thus, for the filtered beam, the HVL (0.41 mm Al) agrees within 3 percent with the calculated HVL (0.40 mm Al) for 17.4 keV photons. This close agreement demonstrates the quasi-monoenergetic nature of the Mo-filtered x-ray beam.

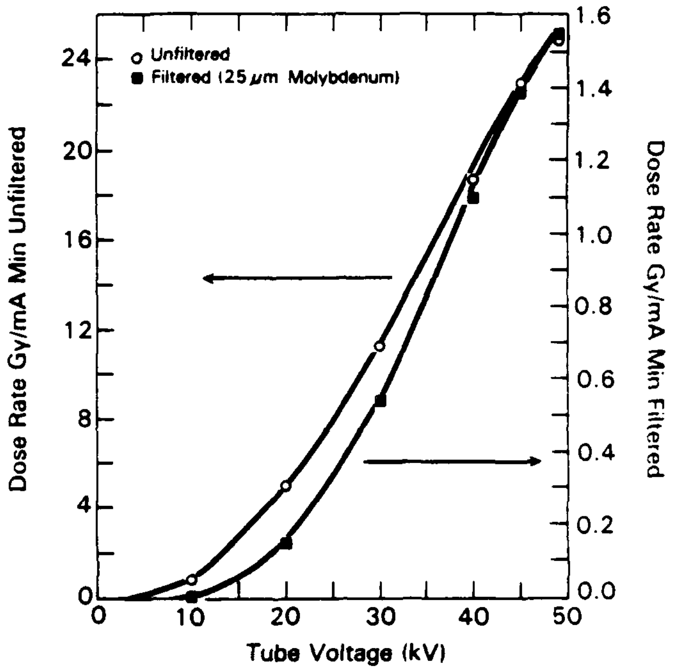


Figure 5. Dose rate vs. potential difference (kV) with a constant current normalized to 1 mA for filtered and unfiltered tubes.

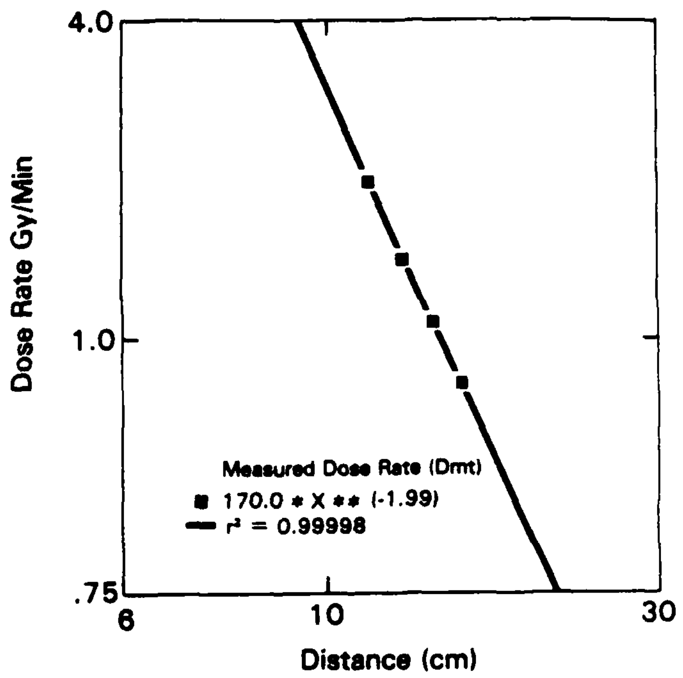


Figure 6. Dose rate vs. distance (focus-to-surface distance). Slope of the line, -1.99 vs. expected -2.0, confirms expected inverse square behavior of x-ray output. See table 3 for details.

Table 3. Radiation Dose Rates

Tube Scale Indicator	TDD* (cm)	FSD† (cm)	Gy/min
0	5.0	10.7	1.54
I	6.0	11.7	1.28
II	7.0	12.7	1.10
III	8.0	13.7	0.94

*TDD: tube-detector distance, which is measured from the end of the tube to the surface of the detector. The tube scale indicator is marked to allow easy and accurate variation in the TDD.

†FSD: focus-to-surface distance, which is the sum of the TDD plus 5.7 cm (the distance from the end of the tube collimator to the Mo target). The 5.7-cm distance was provided by the tube manufacturer.

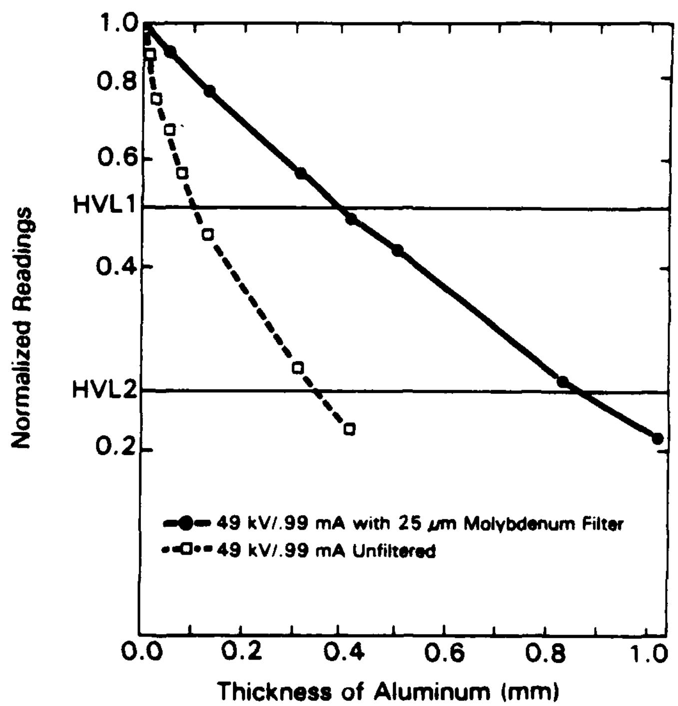


Figure 7. Half-value layer measurements for filtered and unfiltered tubes.

BEAM UNIFORMITY AND PENUMBRA

As indicated in the Dosimetry Procedures section, radiographs of the nine collimated beams and the open beam were taken and analyzed. Table 4 summarizes the results of the beam diameter measurements for the horizontal and vertical axes with a focus-to-surface distance of 10.7 cm.

The diameter in the vertical axis was in all cases greater than that in the horizontal axis because of the requirement of radiating at a 35^{o} angle. Because of constraints imposed by the electrophysiology apparatus, it was necessary to angle the tube at 35^{o}. Since the radiation must be conducted at an angle, the beam is ellipsoidal.

Table 4. Collimated Field Sizes

	Diameter (mm)	
Collimator	Horizontal	Vertical
A	25	27
B	21	23
C	13	15
D	05	06
E	24	26
F	18	20
G	11	13
H	05	06
I	22	24
OPEN	26	27

Preliminary density scans of the film showed that the optical density in the center of the beams varied less than 5 percent between the various collimators. Also, each beam profile appeared to be of uniform density with no artifacts other than a surrounding penumbra region. From these results it was concluded that the dose rate was approximately the same for all collimators, so that the output data for the OPEN beam applied to all other beam sizes. This finding was particularly important because of the relatively large diameter (16 mm) of the ionization chamber used to measure dose rates. Further analysis of the OPEN beam was conducted using the Drexel Image Processing Center Brain software package (see figures 8 and 9).

In the horizontal direction, the penumbra region was 8 mm wide on both sides of the main beam (i.e., the 26-mm region). During dose measurements, it was crucial to keep the ionization chamber out of this region. The vertical analysis provided integral information in the area of tissue positioning.

Another effect of angling the tube is that the beam intensity varied according to inverse square. Quantification of the film's density in the 27-mm vertical region indicated an optical density of 0.59 in the center of the beam. Due to inverse square, the density closest to the tube was 0.61; the density farthest from the tube was 0.56. The difference in output relative to the center of the beam, at which the doses in table 3 are quoted, could vary from 3 to 5 percent.

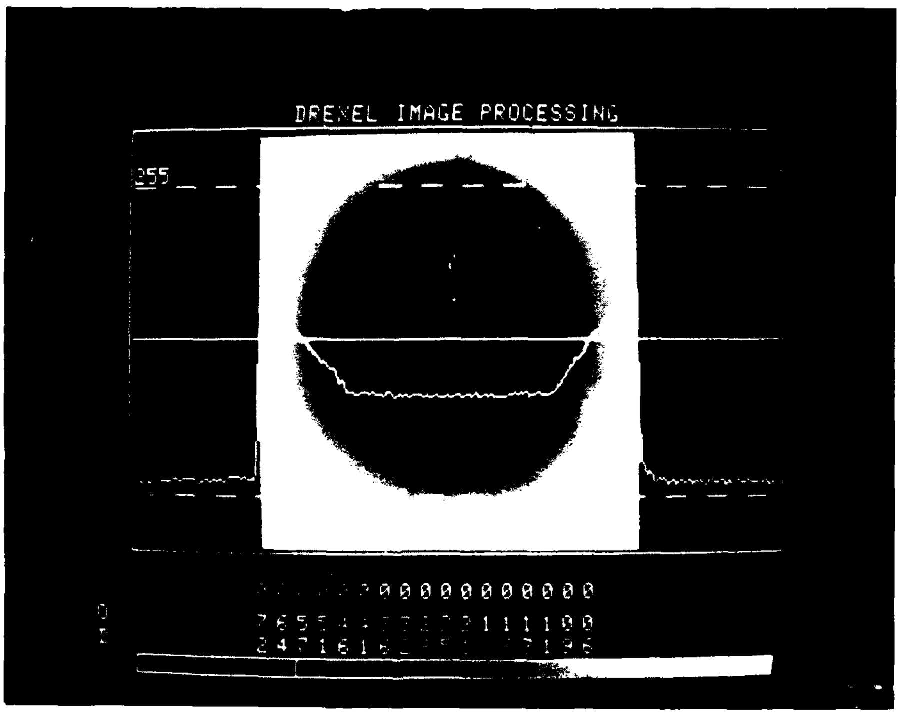


Figure 8. Beam uniformity and penumbra analysis in the horizontal axis. Optical density is constant across the field.

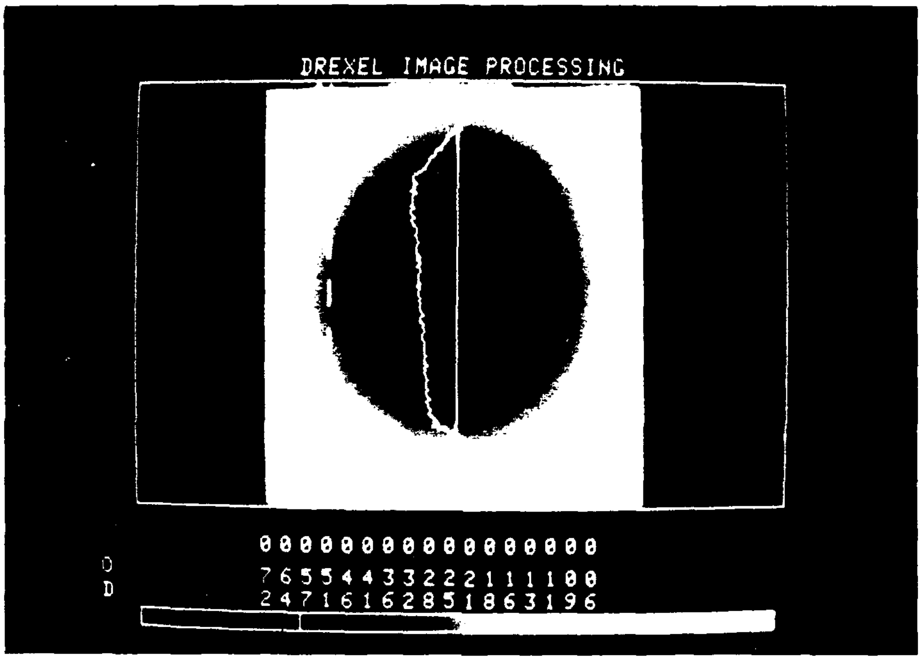


Figure 9. Beam uniformity and penumbra analysis in the vertical axis. Because of the 35° angle of the x-ray tube during radiation, optical density is greater close to the tube and less as distance increases, relative to the center of the beam. Dose rates across the useful area of the beam vary from 3 to 5 percent.

DEPTH DOSE

Depth-dose measurements were done by positioning sheets of lucite on top of the Capintec chamber. The referenced mass attenuation coefficient for lucite (0.835 cm^2/g) (9) for approximately 17.4 keV photons was in close agreement with the experimental measurements (figure 10).

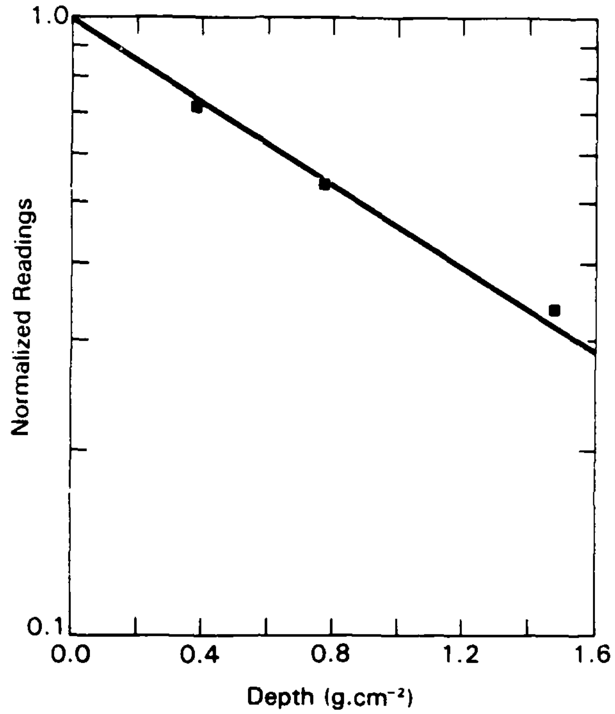


Figure 10. Depth dose through lucite. Slope of the line is -0.77 cm^2/gm, which agrees with referenced mass attenuation coefficient for 17.4 keV photons in lucite to within 8 percent (see table 2). Referenced value includes coherent scattering, which, it is believed, accounts for much of the disparity.

RADIATION SAFETY SURVEY

A comprehensive radiation safety survey was conducted to evaluate the primary and secondary protective barriers for the primary beam and leakage/scatter (10). A multistep survey process was conducted and included the following:

- Film studies around the tube head verified its shielding integrity.

- Lead sheets and lead overlaps were examined visually at all edges and joints.

- A qualitative shield survey was conducted with ^{99m}Tc (technetium) and a pancake Geiger-Müller (GM) counter.

- A quantitative shield survey was conducted with x rays at maximum kV and mA in the actual scatter geometry, using a GM tube to find hotspots and an ionization chamber to measure mR/hr.

The maximum radiation leakage of <0.5 mR/hr quoted by the x-ray tube manufacturer (appendix B) was confirmed using a Victoreen 471 survey meter in contact with the tube while operating at maximum power. Additionally, film studies were conducted around the tube, and results were negative for pinhole leakage.

Visual examination of all lead sheets/overlaps before operation each day was imperative. Because of the malleable characteristic of lead, the joints and edges can bend, and streaming could occur. The Standard Operating Procedures (appendix C) emphasize the need to visually inspect the entire cage as part of the routine start-up procedure.

For the qualitative survey, an unshielded vial containing 4 mCi of ^{99m}Tc was positioned in the lead box, and a sensitive GM survey meter was used to locate any hotspots. During the initial survey, readings of up to 5 mR/hr were noted at the edges and joints. Accordingly, the cage was modified to ensure that no readings above background were obtained outside the lead box.

Last, the quantitative survey was conducted with the tube settings at maximum kV and mA. The Victoreen 471 survey meter was used with particular attention given to the joints and edges. The modifications mentioned above were sufficient as no readings above 0.05 mR/hr were noted.

DISCUSSION

This system provides a unique radiation capability with built-in flexibility that allows the investigator to observe even the most subtle changes. Further, the quantitative study of radiobiological damage on the cellular level is much easier. The following are some additional advantages of the system:

- The entire unit is in the lab, under the user's control. Radiations can be performed whenever the biological system is ready.

- Simultaneous radiation and observation of the sample, both visually and by microelectrodes.

- Variable dose rates.

- The tube is easily removed with highly reproducible dose rates after repositioning.

- Various collimators are provided to give selected beam diameters.

- The Mo-Mo target/filter system gives an excellent compromise between high-dose rate and acceptable penetration ability of the beam. The x-ray energy spectrum is quasi-monoenergetic with well-defined radiation quality.

• The x-ray tube is extremely small and operates at low power with no external cooling system. The x-ray tube is also capable of versatile positioning in a complicated experimental apparatus.

• During tube operation, no electrical interference is noted on electrophysiology recordings.

This unit is a prototype, and with such a system come many learning experiences. Some recommendations for future improvements are as follows:

• Encase the lead sheets in plywood to avoid possible sagging problems.

• Install a shutter to eliminate the radiation dose delivered during the brief, 1-minute warm-up time (see appendix C). For high-dose radiations (>6 Gy), the warm-up dose is negligible (<1 percent) compared to the total dose delivered. However, for low-dose radiations, special accounting may be necessary for the dose delivered during the brief warm-up period.

• Improve the alignment and positioning mechanism to give more versatile beam location.

• Develop the capability to deliver dose rates as high as 20 Gy/min.

• Acquire a smaller diameter parallel-plate ionization chamber, which, from a dosimetry perspective, would be advantageous in dealing with a narrow beam.

• Install a rugged and submersible beam intensity monitor for active in-beam dosimetry, such as a small (<1 mm^3) plastic scintillation detector.

The x-ray apparatus described in this report is currently being used to conduct local in vitro radiations of the hippocampal region of guinea pig brains. Preliminary quantification of the electrophysiological response indicates the apparatus is suitable for this application.

ACKNOWLEDGMENTS

Designing and constructing this new radiation facility could not have been done without the cooperation and hard work of a large number of individuals. Particular appreciation is due to Norman Rich, M.D., COL Kenyon Kramer, MC, USA, and CDR Jerry Thomas, MSC, USN, for their assistance in acquiring the unit; Don Gotthardt, Don Stevens, and Frank Sharpnack for the design and fabrication of the radiation system; Darrell Grant and Dave Morse for their art and photographic support, respectively; Jerald Bond for the radiation safety analysis; Lt Col G. Andrew Mickley, USAF, SGT Tom Nemeth, USA, and Ed Movius, M.D., for their assistance with the Drexel Image Processing system; and Doug Eagleson and Scott Hawkins for their support with some of the graphs and formatting. Special thanks to Modeste Greenville and Carolyn Wooden for editing and preparing the report.

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APPENDIX A. NBS CALIBRATION REPORTS

DG 8454 85
TFN G45095
1985 OCT 30

U. S. DEPARTMENT OF COMMERCE

NATIONAL BUREAU OF STANDARDS

GAITHERSBURG, MD 20899

REPORT OF CALIBRATION

CAPINTEC CHAMBER

MODEL PS-033 SERIAL NUMBER CII.334495

MANUFACTURED BY CAPINTEC INSTRUMENT CO.
MONTVALE, NJ 07645

SUBMITTED BY ARMED FORCES RADIOBIOLOGY RESEARCH INSTITUTE
BETHESDA, MD 20814-5145

RECEIVED AT NBS ON 1985 SEP 23

THE CALIBRATION FACTORS GIVEN IN THIS REPORT ARE QUOTIENTS OF THE X- OR GAMMA-RAY EXPOSURE AND THE CHARGE GENERATED BY THAT RADIATION IN THE IONIZATION CHAMBER. CHARGE WAS MEASURED FOR BOTH POLARITIES OF THE STATED POTENTIAL AND THE AVERAGE VALUE WAS USED IN COMPUTING THE CALIBRATION FACTOR. LEAKAGE CORRECTIONS WERE APPLIED IF NECESSARY. IF THE CHAMBER WAS OPEN TO THE ATMOSPHERE THE MEASUREMENTS WERE NORMALIZED TO ONE STANDARD ATMOSPHERE AND 22 DEGREES CELSIUS. USE OF THE CHAMBER AT OTHER PRESSURES AND TEMPERATURES REQUIRES NORMALIZATION OF THE ION CURRENTS TO THESE REFERENCE CONDITIONS. THE NORMALIZING FACTOR F IS COMPUTED FROM THE FOLLOWING EXPRESSION:

$$F = (273.15 + T)/(295.15\ H)$$

WHERE T IS THE TEMPERATURE IN DEGREES CELSIUS, AND
H IS THE PRESSURE EXPRESSED AS A FRACTION OF A STANDARD ATMOSPHERE. (1 STANDARD ATMOSPHERE = 101.325 KILOPASCALS = 1013.25 MILLIBARS = 760 MILLIMETERS OF MERCURY)

THE EXPOSURE RATE AT THE CALIBRATION POSITION WAS MEASURED BY A FREE-AIR IONIZATION CHAMBER FOR X RADIATION, AND BY GRAPHITE CAVITY IONIZATION CHAMBERS FOR COBALT-60 AND CESIUM-137 GAMMA RADIATION. THE GAMMA-RAY EXPOSURE RATES WERE CORRECTED TO THE DATE OF CALIBRATION, FROM PREVIOUSLY MEASURED VALUES, BY DECAY CORRECTIONS BASED ON HALF-LIVES OF 5.27 AND 30.0 YEARS, FOR COBALT-60 AND CESIUM-137 RESPECTIVELY.

DG 8454/85
1985 OCT 30

THE UNCERTAINTY OF THE EXPOSURE-RATE MEASUREMENTS IS BELIEVED TO BE WITHIN ONE PERCENT AND THE ION CURRENT MEASUREMENTS ARE BELIEVED TO BE ACCURATE TO WITHIN A FEW TENTHS OF ONE PERCENT.

THE CALIBRATION FACTOR IS GIVEN TO FOUR DIGITS TO PREVENT ROUNDING ERRORS UP TO 0.5 PERCENT WHEN THE FIRST DIGIT IS UNITY.

INFORMATION ON TECHNICAL ASPECTS OF THIS REPORT MAY BE OBTAINED FROM J. T. WEAVER OR P. J. LAMPERTI, RADIATION PHYSICS C210, NATIONAL BUREAU OF STANDARDS, GAITHERSBURG, MD 20899, (301) 921-2361.

REPORT REVIEWED BY

REPORT APPROVED BY R. LOEVINGER RL

FOR THE DIRECTOR
BY

Randall S. Caswell

RANDALL S. CASWELL
CHIEF, IONIZING RADIATION DIVISION
CENTER FOR RADIATION RESEARCH
NATIONAL MEASUREMENT LABORATORY

DG 8454 85
1985 OCT 30

NATIONAL BUREAU OF STANDARDS REPORT OF CALIBRATION

ARMED FORCES RADIOBIOLOGY RESEARCH INSTITUTE
BETHESDA. MD 20814-5145

CAPINTEC CHAMBER
MODEL PS-033 SERIAL NUMBER CII.334495
OPEN TO THE ATMOSPHERE WHEN TESTED
WALL POTENTIAL WAS + AND - 300 VOLTS WITH RESPECT TO INNER ELECTRODE

BEAM CODE	HALF-VALUE LAYER AL (MM)	CU (MM)	CALIBRATION FACTOR 22 DEG C AND 1 ATM	DIST (M)	BEAM SIZE (MM)	EXP RATE (R/S)
L20	.07		6.349E+09 R/C	.50	C 43	1.2E+00
L50	.75		6.502E+09 R/C	.50	C 43	2.6E-01
M300	21.90	5.3	*6.723E+09 R/C	.78	C 26	6.0E-02
CO-60		14.9	*6.970E+09 R/C	1.46	S 63	4.2E-01

DURING CALIBRATION THE CAVITY WAS POSITIONED IN THE CENTER OF THE BEAM WITH THE STEM PERPENDICULAR TO THE BEAM DIRECTION. THE WINDOW FACED THE SOURCE OF RADIATION.

3.E-15 AMPERES WAS THE LEAKAGE CURRENT MEASURED BEFORE CALIBRATION.

.998 WAS THE RATIO OF THE AVERAGE FOR BOTH POLARITIES OF THE CURRENTS MEASURED AT FULL COLLECTION POTENTIAL, TO THE AVERAGE FOR HALF COLLECTION POTENTIAL FOR A CURRENT OF 7.5E-12 AMPERES. A DETAILED SATURATION STUDY WAS NOT CARRIED OUT AND NO CORRECTION FOR LACK OF SATURATION WAS APPLIED TO THE DATA.

1.2% WAS THE LARGEST DIFFERENCE BETWEEN THE CURRENTS MEASURED FOR FULL POSITIVE AND NEGATIVE COLLECTION POTENTIALS. THIS OCCURRED FOR THE BEAM QUALITY M300.

* THE CHAMBER WALL THICKNESS WAS INCREASED FOR THIS BEAM QUALITY BY ADDITION OF THE SHELL SUPPLIED WITH THE CHAMBER.

NOTE: THE REFERENCE PLANE FOR THIS CHAMBER WAS THE FRONT SURFACE OF THE PLASTIC BODY FOR BEAM CODES L20 AND L50, AND THE FRONT SURFACE OF THE EQUILIBRIUM SHELL FOR BEAM CODES M300 AND CO-60.

CHECKED BY P. Lamperti

DG 8438/85
TFN G44975
DB 819:151
1985 SEP 06

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
GAITHERSBURG, MD 20899

REPORT OF TEST

Keithley Electrometer
Model 616
Manufactured by Keithley Instrument Company
Cleveland, OH 44137

Electrometer Serial Number 163817

Submitted by Armed Forces Radiobiology Research Institute
Bethesda, MD 20814

Received at NBS on 1985 AUG 09

The referenced electrometer has been tested for use with the ionization chamber covered by Report of Calibration DG 8425/85. The system was tested for the following combination of switch positions:

Switch	Position
Function	10^{-9} C
Mode	Fast
Sensitivity	Auto
Bias	N/A
Input	N/A
Background	N/A

When the electrometer charge measurements were corrected by K_Q, where

$$K_Q = 0.986$$

measurements with the system using Beam Code Co-60 were found to be consistent with the calibration factor in DG 8425/85. K_Q was determined by injecting a known charge into the electrometer input and observing the corresponding change in the charge reading. The value of the injected charge is believed to have an uncertainty of less than 0.1%.

The exposure in air at the reference point of the ionization chamber, with the chamber replaced by air, is given by

$$X = K_Q\ F\ Q\ N = 0.986\ F\ Q\ N$$

where

N is the chamber calibration factor in terms of exposure per unit charge, for stated conditions of calibration;

Q is the change in charge on the electrometer system as indicated by the digital panel-meter readings, using the tested combination of switch positions; and

F is a factor that normalizes the measurements to the temperature and pressure reference conditions for N. F is defined in Report of Calibration DG 8425/85.

Information on technical aspects of this report may be obtained from P. J. Lamperti, Radiation Physics C210, National Bureau of Standards, Gaithersburg, MD 20899, (301) 921-2361.

Measurements supervised by P. J. Lamperti PJL

Report approved by R. Loevinger RL

For the Director
by

Randall S. Caswell

Randall S. Caswell
Chief, Ionizing Radiation Division
Center for Radiation Research
National Measurement Laboratory

APPENDIX B. TUBE SPECIFICATIONS

kevex

KEVEX TUBE DIVISION

320 EL PUEBLO
P.O. BOX 66860
SCOTTS VALLEY, CA. 95066 * TEL: (408) 438-5279

FINAL TEST DATA SHEET FOR X-RAY PRODUCTS

MODEL K 5010TMo S/N 3183

TARGET MATERIAL MOLY

TEST CONDITIONS:

TARGET VOLTAGE	50	KILOVOLTS DC
TARGET CURRENT	1.0	MILLIAMPERES DC
FILAMENT VOLTAGE	6.3	VOLTS RMS (REF)
AMBIENT TEMPERATURE	22 +/- 2	DEGREES CENTIGRADE
WARM-UP PERIOD	30	MINUTES MINIMUM

TESTED WITH: K 5010 P/S S/N 1500

TEST STAND A - SI(LI) DET. (X) TEST STAND B - SCINT. DET.

LONGTERM X-RAY OUTPUT STABILITY:

BETTER THAN .08 % COEFFICIENT OF VARIATION
IN ANY 4-HOUR PERIOD OVER 24 HOURS

MAXIMUM RADIATION LEAKAGE: <.5 mR/hr
at 1 inch from the surface of housing

MAXIMUM LEAKAGE CURRENT: N/A uA at N/A
(with no current programmed)

TESTED BY Paul Praijs DATE 4/21/83

Q. C. INSPECTION [signature] DATE APR 21 1983

APPENDIX C. STANDARD OPERATING PROCEDURES

(Kevex X-ray Unit Model No. K5010T, Serial No. 3183)

The following are the Standard Operating Procedures for the Kevex X-ray Unit being used by the Physiology Department for brain cell irradiations. No deviation from these procedures is authorized unless first approved by the officer in charge, the Radionuclide and X-Ray Safety Committee, or the Safety and Health Department. The procedures emphasize radiation safety and tube preservation, with radiation safety receiving the higher priority.

1. Visual Inspection Safety. Before any irradiations, the operator shall conduct a thorough visual inspection of the following:

a. Faraday cage. Examine the top and bottom of the cage, all door corners, the front junction, and all edges to ensure that all lead shielding is intact.

b. All interlocking mechanisms (addressed in paragraph 3d).

c. Visual warning light.

d. Control panel.

2. Log Book. In accordance with RSI 530, paragraphs 7b and c, the unit operator log shall be readily available and used for every operation of the unit. An entry must be made for each run, except that one entry may be used for a series of identical runs if the number is clearly specified in the log. Log entries shall include the following:

a. All machine settings (time, kVp, collimation, mA).

b. Operator's name.

c. Description of use and special conditions.

d. Date and time.

3. Warm-up Procedure for the X-Ray Tube. While preparing the array for radiation, warm up the tube using the following procedure:

a. Ensure that the front doors are properly closed and secured with the latch-bar.

b. Ensure that the switch on the grey box is in the ON position and the warning light is activated.

c. Insert the operation key in the control panel and turn it ON to provide AC power to the control panel.

d. With the tube settings at 0 kV/0 mA and the red x-ray light illuminated on the control panel, trip the interlock to ensure that the unit shuts down. Unit shutdown will include the following:

(1) Red light on top goes OFF.

(2) Red x-ray ON light on the control panel goes OFF.

(3) Green x-ray OFF light illuminates.

NOTE. IF THIS DOES NOT OCCUR, CEASE ALL OPERATIONS AND CONTACT THE SAFETY AND HEALTH DEPARTMENT IMMEDIATELY.

e. Ensure that the following steps are adhered to when increasing voltage and current (daily when in use):

Step	kV/mA	Time (min)
1	0/0	Interlock check (paragraph d above)
2	10.0/.10	1
3	20.0/.10	1
4	30.0/.30	1
5	35.0/.30	20
6	40.0/.50	2
7	45.0/.70	2
8	49.0/.99	2

f. When increasing kV/mA, increase the kV first, then the mA. When decreasing the settings, decrease the mA first, then the kV.

g. When increasing kV, be alert to any arcing (an audible "ticking" sound produced in the tube or the power supply). If more than one or two arcs are observed, back the voltage down to the previous voltage and rerun for the designated time. After the time has elapsed, step the voltage back up, and continue the procedure.

NOTE: Tube should never be switched into operation with kV settings greater than one-half their maximum values.

4. Tissue Electrode Positioning. When the warm-up procedure is completed and the array is ready for radiation, the unit may be shut down. At this point, the cage may be opened and the tube temporarily removed to allow ample room for array/electrode positioning. Upon completion, the tube should be repositioned in accordance with the dosimetric parameters determined by the Operational Dosimetry Division.

5. Brain Cell Radiation Exposures. Repeat procedures in paragraphs 3a-c. Because the tube should NEVER be switched into operation with kV settings greater than one-half their maximum values, ensure that the following steps are adhered to:

Step	kV/mA	Time (min)
1	25.0/.10	1
2	49.0/.99	until desired dose is delivered

This procedure will involve a slight rise time with the cells in place, but at high doses it will be an extremely small percentage of the total dose delivered.

6. Shut Down. The operator shall ensure that at the end of the radiation exposure all equipment as well as the operator key is properly secured.

7. Musts

a. The operator must remain in the room at all times when the key is in the power supply.

b. The key must be kept in the control of a qualified operator and may not be left in the power supply.

c. The operator shall wear proper personnel dosimetry as required by RSI 530.

8. Posting of the Area. The area shall be posted in accordance with RSI 530, paragraph 7d.

9. Access to the Area. Access to the area is not restricted while the unit is in operation.